

THE ELECTRA KRF LASER SYSTEM *

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Abstract

This paper presents a brief overview of the Electra laser system and reports on the most recent results. The laser system consists of an electron beam pumped main amplifier with an aperture of 30x30 cm², an e-beam pumped 10x10 cm² pre-amplifier, and a KrF discharge laser serving as the seed oscillator. Full laser system shots have been completed with laser energies of 452 J. In addition, 25,000 continuous shots at 2.5 Hz from a single sided diode into laser gas have been achieved with the main amplifier operating as an oscillator.

I. INTRODUCTION

Electra is an electron beam pumped KrF laser system at the Naval Research Laboratory used to advance the technology towards a KrF laser driver for inertial fusion energy [1-7]. Electra consists of two e-beam pumped amplifiers and one commercial discharge laser. The main amplifier includes two identical pulsed power systems, each with a capacitor bank, a 1:12 step-up transformer, parallel pulse forming lines, and laser triggered output switches. Each system generates a 500 kV, 110 kA, 140 ns e-beam that pumps the laser gas from two sides. Depending on the cathode and hibachi (laser gas/vacuum interface structure) configuration, the laser output energy ranges from ~300 to ~700 J per shot. Operating as a laser oscillator, the main amplifier has run at repetition rates of up to 5 Hz, and has operated at 2.5 Hz for 25,000 continuous shots.

The pre-amplifier pulsed power system utilizes a fast 10-stage Marx, pulse forming lines, and a magnetic switch. The system powers two diodes, of which each operates at 175 kV, 70 kA, and 50 ns [8]. Initial pre-amplifier laser experiments with a first generation cathode and hibachi, and with a 0.5 J discharge laser serving as the seed oscillator, produced a yield of up to 25 J [9].

This paper will discuss the performance of the pulsed power systems, cathodes and electron beams, thermal management of the pressure foils, hibachi development, and present results of the overall laser system.

II. ELECTRA KRF LASER PROGRAM

The key components under development are a durable electron emitter; a long-lived pressure foil structure (hibachi); a laser gas recirculator; and optical windows (see Fig. 1). There is also an ongoing program in the physics of KrF lasers [10]. All of these components affect the efficiency and durability of the overall laser. In addition, the durability of some laser components are interlinked, e.g., the durability of the pressure foil is in part dependent on the performance of the pulsed power system and the cathode. The following subsections will discuss some of the KrF laser components in more detail.

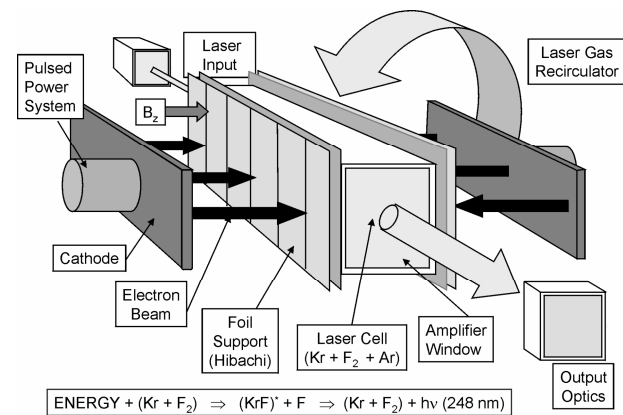


Figure 1. The main components of an electron beam pumped KrF laser.

A. Pulsed Power Systems

Each of the two pulsed power systems of the main amplifier consists of a capacitor bank that feeds the primary side of a 1:12 step-up transformer. The secondary side charges a pair of coaxial, water dielectric, pulse forming lines. The energy in the lines is then switched into the vacuum diode (load) using laser-triggered output switches. The system operates at 400-550 kV, 70-120 kA, 140 ns FWHM pulse duration, and rep-rates of up to 5 Hz [11]. Erosion of the output switch electrodes require a refurbishment every 50,000 to 100,000 shots. This first

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generation system serves as a test bed to develop the KrF laser components on the main amplifier, while the next generation pulsed power system is developed on the pre-amplifier.

Spark gap switches need to be eliminated to improve the durability and efficiency of the pulsed power system. The 175 kV, 80 kA pre-amplifier uses a fast 10-stage Marx, pulse forming lines, a magnetic switch, and transit time isolators. Currently, the Marx uses spark gaps with electrode lifetimes of 100,000 shots. The system operates at rep-rates of up to 5 Hz and with a jitter of less than 900 ps. Two solid-state switches are presently under evaluation for replacement of the spark gaps: (a) laser gated and pumped thyristors that are under development by L3 Communications [12] and (b) the Applied Pulsed Power thyristor switches, Model S33 [13].

B. Cathode and Electron Beams

The cathode in the main amplifier requires a fast risetime (< 40 ns), uniform current emission without hot spots, low plasma generation in the A-K gap to prevent diode impedance collapse, and a current density of 30-50 A/cm² at a rep-rate of 5 Hz. Moreover, the cathode system needs to be simple, durable, and efficient. Initial experiments were performed with a low-cost double density velvet cloth to develop a cathode configuration for efficient electron beam transport through the hibachi into the laser gas. With a counter-rotated strip cathode, (which maximizes efficiency by patterning the electron beam to miss the hibachi ribs) about 70% of the flat top diode electron energy has been deposited in the laser gas of the main amplifier. This is with 500 kV electrons and a 25 μ m thick stainless steel foil [14]. At 800 kV, the electron beam energy envisioned for a full scale system, the electron energy deposition efficiency is expected to be closer to 80%.

Most of our cathode development has been carried out with monolithic cathodes, in which the hibachi ribs intercept a large fraction of the electron beam energy [14]. Cathodes with pure velvet emitters have limited lifetimes: a few 100's of continuous shots at rep rates of 1 to 5 Hz, after which the cathode showed "burned" spots of the velvet cloth that most likely produced highly non-uniform electron emission (i.e., hot spots). The durability of the velvet cathode was significantly improved by placing a 5 cm thick cordierite ceramic honeycomb about 2 mm above the velvet cloth [15-16]. The ceramic honeycomb/velvet cathode showed sufficient robustness to allow continuous operation of up to 10,000 shots at 1 and 2.5 Hz.

The velvet cloth was replaced with a carbon fiber cathode made by Energy Science Laboratories, Inc. [17], which further increased the durability of the ceramic honeycomb cathode. The ceramic honeycomb/carbon fiber cathode was tested for 5 x 10,000 shots over 5 consecutive days without breaking the diode vacuum, as well as 25,000 continuous shots at 2.5 Hz from a single sided diode into laser gas. Additional cathode improvements are currently underway, which include

cooling of the cathode back plate, modifications of the ceramic honeycomb construction, and the coating of the cordierite to further enhance its robustness.

C. Pressure Foil Cooling

The pressure foil separates the atmospheric laser gas from the vacuum diode. This metal foil should be low in both density and thickness to reduce absorption of the electron beam energy. For enhanced durability, the pressure foil requires high mechanical strength, ductility, and resistance to fluorine. The electron beam deposits some fraction of its energy in the foil resulting in an increase in foil temperature, while the mechanical strength of the foil is reduced at higher temperatures. Therefore, cooling is essential to keep the foil below its long-term fatigue stress limits.

Foil cooling experiments have identified three successful techniques: (a) Forced convective cooling by the recirculating laser gas with the addition of up to 10% of helium. It was found that helium showed a negligible reduction of the laser energy output. In this application the laser gas velocity along the foils was increased with a fixed "v-plate" that forces all the laser gas flow through narrow slots before traversing the foil [19]. (b) Forced convective cooling by gas jets below the e-beam pumped region. (c) Cooling by a water mist trapped between two foils. Techniques (b) and (c) have been developed by Georgia Institute of Technology and tested on Electra's main amplifier. An infrared pyrometer has been used to measure the foil temperature. All three techniques have shown to keep the temperature of the 25 μ m thick stainless steel foil below 280°C, with a monolithic cathode. It is projected that the foil temperature will be below 450°C with the high efficiency cathodes operating at 5 Hz. This is below the long-term thermo-mechanical fatigue limit of the stainless steel foil.

D. Hibachi Development

During assembly, the existing hibachi produces a flat foil that covers the hibachi ribs. When pressure is applied to the foil (i.e., 1.36 atm. on the laser cell side and vacuum in the diode for the main amplifier), the foil stretches by several millimeters into the hibachi rib opening; this stresses the foil past its elastic limit and induces a three dimensional stress at the corners of the rib opening. We have developed a new "scalloped hibachi" in which the foil stresses are significantly lower and are purely cylindrical, i.e., two dimensional. A section of the pre-amp scalloped hibachi frame is shown in Figure 2. The most challenging part of the scalloped hibachi is a reliable vacuum seal between the hibachi and the foil.

Extensive tests have been performed with gaskets and o-rings and reference [20] provides more detail. To minimize the machining cost of the scalloped hibachi and increase the reliability of the vacuum seal, a round bottom o-ring groove with a quad o-ring has been selected. The o-ring groove with a round bottom can be manufactured on a standard milling machine, using a ball end mill. Furthermore, the quad o-ring stays pressed into the simple

round bottom groove during the hibachi assembly as shown in Fig. 2. The quad o-ring has two sealing surfaces on the foil and up to 4 seals in the o-ring groove. This arrangement has been successful with all foils tested on a scalloped test hibachi, including a 25 μm thick aluminum foil.

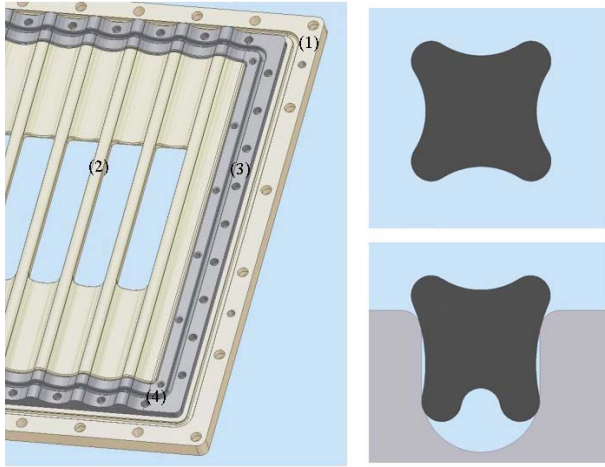


Figure 2. Left side: Scalloped pre-amp hibachi frame with (1) titanium frame, (2) water-cooled hibachi ribs, (3) stainless steel foil clamping frame, and (4) o-ring groove for vacuum foil seal. Right side: Quad o-ring without and within the o-ring groove.

E. Laser Operation

The main amplifier of Electra is operated as an oscillator by using a rectangular flat mirror (32x36 cm^2) with a 98.5% reflectance coating at 248 nm and a parallel, uncoated fused silica output coupler (33x35 cm^2) that provides a reflection of 8% (total of both surfaces). Two single sided, 248 nm AR coated windows, tilted at 14 degrees, enclose the laser cell with their uncoated surfaces exposed to the laser gas.

The main amplifier, with a gas composition of 39.7% Kr, 60% Ar and 0.3% F_2 at a total pressure of 1.36 atm,

produced average output energies greater than 700 J with strip cathodes and ~ 300 J with the less efficient monolithic cathodes. Currently, long rep-rated runs are performed with monolithic ceramic cathodes. The ceramic cathode will be patterned into strips after cathode improvements as described in section II.B. are completed.

A LPX 305i (Lambda Physik) KrF discharge laser has been used to seed the pre-amplifier with 0.5 J [9]. The subsequent output from the pre-amp is up to 25 J. For these initial experiments, the pre-amplifier with a laser aperture of 10x10 cm^2 used monolithic velvet cathodes and a simple hibachi without an attempt to pattern the electron beam. This results in a low efficiency system. Laser gas mixture was 19.7% Kr, 80% Ar and 0.3% F_2 at a total pressure of 1.09 atm. Output laser energies of more than 30 J are expected with more efficient next generation hibachis and strip cathodes.

Initial tests have been performed with the entire laser system as shown in the schematic of Fig. 3. The 0.5 J seed laser beam is angular multiplexed [21] into two beams and then amplified by the pre-amp. The output of the pre-amp is further multiplexed into a total of 6 beams, each with an average pulse duration of ~ 20 ns, which are sequentially amplified by the main amp. A total single shot laser output energy of 452 J has been achieved, and the laser system has been successfully rep-rated in a burst of 5 shots @ 5 Hz averaging 300 J per pulse.

III. SUMMARY

The Electra laser program has been successful in advancing the technologies required for a durable and efficient KrF laser. Current achievements include high electron beam deposition efficiency into the laser gas, successful hibachi thermal management using forced convective cooling that will maintain the foil below stress limits at 5 Hz, and an advancement in durability of the overall laser system by attaining 25,000 continuous shots at 2.5 Hz on the main amplifier. Initial full laser system

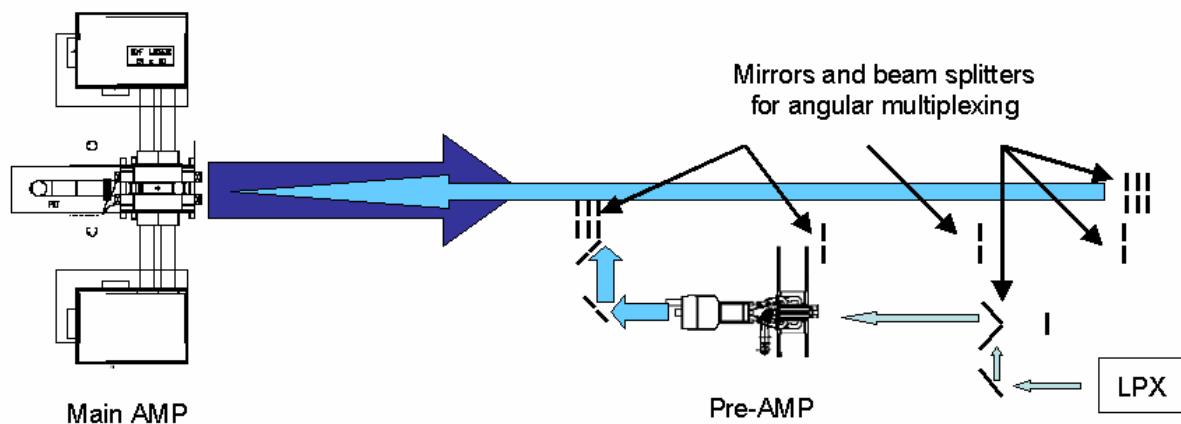


Figure 3. The Electra KrF laser system with the LPX KrF discharge laser, the pre- and the main amplifiers. Angular multiplexing is used to increase the total laser input pulse durations match the electron pump pulse duration of each amplifier. Details of the multiplexing with time delay are not shown for clarity.

shots have achieved a laser energy of 452 J. Future work will include the continuing development of the durable, high performance ceramic cathode, and an advanced scalloped hibachi.

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